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requirements on shipborne PNT data; accuracy, integrity; simulation; AIS; risk on incidents and accidents; ship domain; ship arena

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INTERDEPENDENCIES BETWEEN EVALUATION OF COLLISION RISKS AND PERFORMANCE OF SHIPBORNE PNT DATA PROVISION

Summary. The highest priority for safe ship navigation is the avoidance of collisions and groundings. For this purpose, the concept of ship domain has been introduced to describe the surrounding effective, waters which should be kept clear of other ships and obstacles. In the last decades, a large variety of ship domains have been developed differing in the applied method of their determination as well as in the modelled shape, size, and safety areas. However, a ship domain should be adjusted in real time to enable a reliable evaluation of collision risks by the officers of the watch. Until today in discussions about modelling and utilization of ship domains, it has been mostly unnoticed that the performance of vessel's position (P), navigation (N), and timing data (T) ultimately determines the accuracy and integrity of indicated ship domain. This paper addresses this question, and starts with a comprehensive analysis of AIS data to prove the violation of ship domains in the maritime practice. A simulation system has been developed to enable, for the first time, investigation into the extent inaccuracies in PNT data result to a faulty evaluation of collision risks. The simulation results have shown that there is a non-negligible risk of not detecting a collision, if inaccuracies of sensor data remain unnoticed.

ZALEŻNOŚCI POMIĘDZY OCENĄ RYZYKA ZDERZEŃ STATKÓW A JAKOŚCIĄ DANYCH DOSTARCZANYCH PRZEZ POKŁADOWE SYSTEMY PNT

Streszczenie. Zapobieganiu wypadkom na morzu przyznaje się najwyższy priorytet w ramach bezpiecznego prowadzenia statku. Dla poprawy bezpieczeństwa żeglugi stworzono koncepcję domeny statku. Definiuje ona taki obszar wokół jednostki pływającej, w którym nie powinno być ani żadnych innych uczestników ruchu morskiego, ani przeszkód. Na przestrzeni minionych dziesięcioleci powstały rozmaite domeny statku różniące się między sobą sposobem ich definiowania, modelowaniem kształtu, rozmiarem czy strefami bezpieczeństwa. Istotnym warunkiem do należytej oceny ryzyka kolizji jest umożliwienie oficerowi wachtowemu dopasowania w czasie rzeczywistym domeny statku do panujących warunków. W dotychczasowych dyskusjach na temat modelowania i stosowania domeny statku przeważnie pomijano istotną zależność pomiędzy dokładnością pozycji statku (P), wektora ruchu (N) oraz znacznika czasu (T) a dokładnością i spójnością domeny statku. W niniejszym artykule poruszono kwestię powyższego związku. Na wstępie przeprowadzono dogłębną analizę danych AIS i dowiedziono się, że naruszanie domeny statku ma miejsce w praktyce żeglugowej. Ponadto opracowano system symulacyjny, który po raz pierwszy umożliwia badanie wpływu niedokładności danych PNT na błędność oceny ryzyka kolizji. Wyniki symulacji potwierdziły, że istnieje poważna możliwość niewykrycia groźnej sytuacji zbliżeniowej, jeżeli pozostanie niedostateczna dokładność czujników pokładowych niezauważona.

1. INTRODUCTION

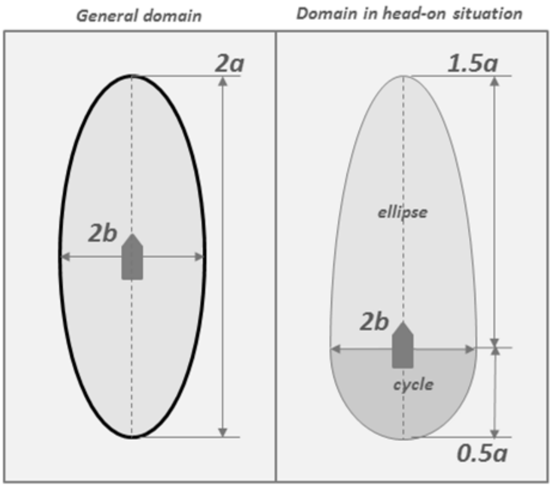
1.1. Background

Collisions and groundings can be effectively avoided, if the bridge team is able to ensure that their ship domain is currently and prospectively free from other traffic participants and obstacles. The ship domain has been defined by Goodwin [2] as ‘‘the surrounding effective waters which the navigator of a ship wants to keep clear of other ships or fixed objects.” The ship arena was introduced by Davis et al. [12]. It describes a larger area around the ship, other than her domain, whereby the size is derived from the needed time of taking collision avoiding actions. Other traffic participants moving into and within the area of ship arena will be evaluated by how far they could violate the ship domain by maintaining the current course and speed. The size and attitude of the ship domain in the traffic area depends on the domain model applied, as well as the determined ship's position and attitude. The ship arena is derived from the ship domain and takes into account the movement of the ship and her manoeuverability. The evaluation of collision risk requires that the position, attitude and movement of all traffic participants entering the ship arena should be known. Consequently, the performance of shipborne PNT data provision is an additional factor influencing the reliability of Decision Support Systems (DSS) used for collision avoidances. Its relevance will be discussed in this paper.

1.2. Resilient PNT

The need for resilient onboard provision of position, navigation, and time data (PNT) is emphasized in the implementation plan of IMO e-navigation strategy as solution S3 “Improved reliability, resilience and integrity of bridge equipment and navigation information” with the risk control option RCO5 “Improved reliability and resilience of onboard PNT systems” [3]. This is understandable due to the importance of PNT data for risk assessment and collision avoidance in ship navigation and traffic management.

An initial step towards resilient PNT has been realized by the maritime community, with the development of the Performance Standards (PS) for multi-system shipborne radionavigation receiver equipment (MRR). This MRR PS [4] supports the full use of data from current and future radionavigation systems (various GNSS, eLoran, R-Mode), and services (SBAS, DGNSS) to increase the performance of positioning and timing. As a supplementary and necessary step [5], the development of Guidelines for onboard PNT (data processing) unit has been identified. Aim of these guidelines is the specification of data processing principles and functions to operate the combined use of shipborne GNSS receivers (Global Navigation Satellite System), and autarkic systems (e.g. radar, gyrocompass, echosounder with bathymetric data), in a coordinated manner. At present, the development of guidelines is complicated by insufficient and nonhomogenous specification of requirements for shipborne PNT data provision (e.g. accuracy and integrity), taking into account the variety of nautical tasks and navigational applications. The paper investigates how far requirements for shipborne PNT data provision can be derived for DSS dealing with the evaluation of collision risks.



condition	a	b
open sea	4L	1.6L
narrow channel	3L	0.8L

Fig. 1. Fujii's ship domain as ellipse with major and minor axes specified in ship length L
Rys. 1. Domena statku według Fujiiego jako elipsa o osiach zależnych od długości statku L

1.3. Ship Domain and Arena

In the last decade, the concept of ship domain was introduced by Fujii [1], and was further developed to determine traffic capacities [1, 6] to improve risk assessment regarding collision and groundings [7, 8], or to evaluate the feasibility and residual risks of evasive manoeuvre [9,10]. In this context, many ship domain models have been created differing in shape (e.g. circular, elliptical, hexagonal, and polygonal), and distinguishing between sharply delineated domains and fuzzy domains to indicate one or more safety areas.

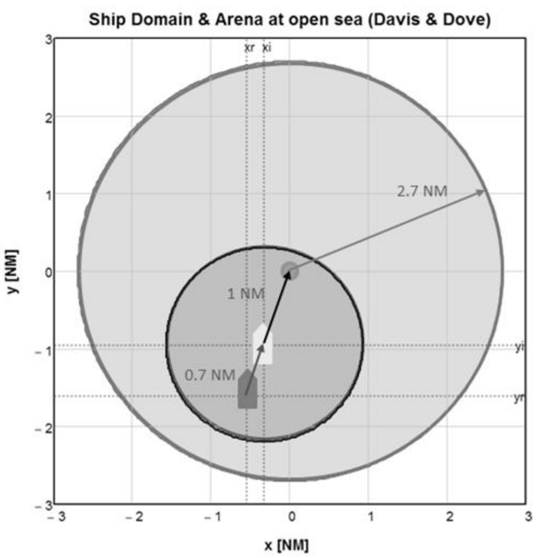


Fig. 2. Ship domain developed by Davis & Dove
Rys. 2. Domena statku według Davisa i Dove'a

Furthermore, different methods have arisen to determine the size of a certain ship domain (e.g. statistical analysis, expert elicitation). Several models consider specific manoeuvre situations (e.g. head-on, overtaking), and take into account the International Regulations for Preventing

Collisions at Sea (COLREG). Therefore, the concept of ship domain should be considered a living tool, serving safety at sea. An overview of the best known developments of ship domain and arena has been given in [10, 13].

As outlined in [7] and shown for Gulf of Finland, the concept of ship domain can be used to detect near collisions. For this purpose, the smallest ship domain has been applied: Fujii's domain for narrow channels (see Fig. 1, [1]). However, using this simple model highlights the following disadvantages [7]:

- the influence of COLREG is neglected,
- the risks of collision passing astern or ahead are considered equivalent, and
- the size of domain is specified in ship lengths.

The ship domain proposed by Davis and Dove [10, 12, 13] ensures that spatial dependencies of collision risks are considered. The associated ship arena illustrates the time needed for taking collision avoidance actions to keep the ship's domain free of other traffic participants.

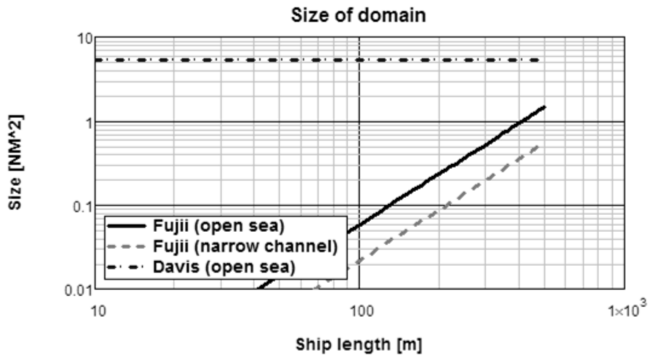


Fig. 3. Size of ship domain as function of ship length
Rys. 3. Wielkość domeny statku jako funkcja długości statku

Currently, the cruiser "ALLURE OF THE SEAS" (LOA=360 m), Ultra Large Container Ships (LOA~400 m), and tanker of the Hellespont-Alhambra-Class (LOA~380 m) are vessels with the greatest ship length overall (LOA). For these ships, the size of Fujii's ship domain (open sea as well as narrow channel) is below the size of Davis's ship domain (Fig. 3). The beam of such large ships can reach values from 40 m to 60 m. The width of Fujii's ship domain in narrow channels has been specified at 1.6 L and is, therefore, independent on ship's beam. For above- mentioned ships, the width achieve values around 600 m and often exceed the navigable waters of harbour approaches and narrow sea channels. This induced the motivation to develop specific ship domains for DSS used in restricted and constrained navigation areas e.g. [14]. We decided to start our investigations with both classic models.

2. AIS-BASED EVALUATION OF INCIDENTS IN THE SOUTHERN BALTIC SEA

2.1. Method used for incident detection

For the simulations, it is important that the subject under investigation corresponds to events or phenomena taking place in real world and reflects them as closely as possible. Before attempting to determine the acceptable inaccuracy range of PNT data by simulating collisions between vessels, it is necessary to assess the approaches between real vessels, in relation to the violations of their ship domains, and the types of areas in which they navigate. The best source of vessel traffic data nowadays, which can support this kind of inquiry, is the Automatic Identification System (AIS).

The AIS data used during incident detection was acquired in August 2014, and obtained courtesy of Federal Waterway Authority (WSV.de). It fully covers the vessel traffic along the German territorial waters. Two separate areas of interest were spatially extracted from the whole AIS data set. First, the open waters located within the Strait of Fehmarn-Belt offered the opportunity to analyse the close encounters between vessels navigating along the major shipping routes connecting the Baltic Sea with the rest of the world. Second, the constrained waters which placed the Kiel Canal lengthwise, from the locks of Brunsbüttel to the locks of Holtenau, produced a set of valuable situations, during which vessels were required to maintain close distances between one another.

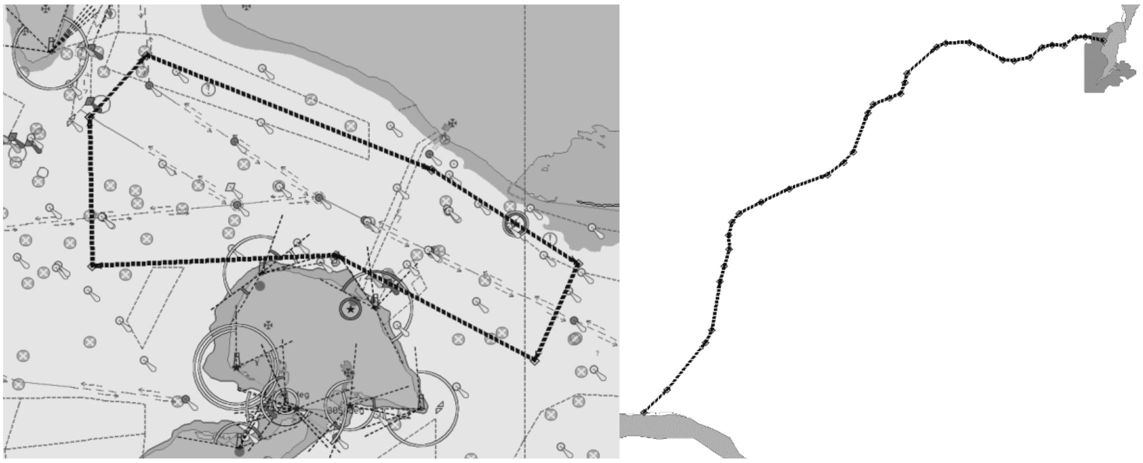


Fig. 4. The Strait of Fehmarn-Belt (left) used to analyse the open waters traffic and the Kiel Canal (right) serving as the "constrained waters" area of investigation

Rys. 4. Cieśnina Fehmarn-Belt (z lewej) jako przykład wód otwartych oraz Kanał Kiloński (z prawej) jako przykład wód ograniczonych w analizie ruchu statków

The dynamic AIS data was first cleaned of sentences which contained default (unknown) data. Then, only the position reports located within one of the above-mentioned areas of interest were selected. For every unique MMSI contained within the dynamic AIS data, a static AIS message was stored, too, in order to obtain the size and type of the vessel. Especially, the dimensions of a vessel are crucial to construct her ship domain.

As it was impossible to acquire the AIS data from all transponders in the given area at the same moment, it was necessary to create a series of snapshots, 180 seconds each, thus allowing the AIS dynamic position reports within an epoch to be no older than 3 minutes. Doing so helped in dealing with the temporary nature of the AIS data, since it is not available at a constant update rate, and depends on the current number of vessels in the area. The time window of 3 minutes was chosen, with respect to the lowest possible update rate specified for the dynamic AIS messages [15]. A time series of such traffic situation snapshots produced the sequences of vessel movements within the areas of interest. Next, the pair of vessels were generated at each traffic snapshot from all available vessels and the distances between them were calculated. As soon as any acquired pair of vessels reached their point of closest approach, its parameters were stored and the ship domains of paired vessels were reconstructed, based on the ship domain parameters listed in Table 1.

Since the domains are ellipses of axes based on LOA to make them more comparable with one another, it was possible to describe the distance at the closest point of approach between a pair of vessels in terms of their domain size, even if smaller or larger than the reference domain. A situation in which a vessel was located inside other vessel's domain was considered a violation, and counted as an incident.

Table 1

Ship domain parameters used during the evaluation of incidents [1]

Area of application	Semi-major axis	Semi-minor axis
open waters (Strait of Fehmarn-Belt)	8×LOA	3.2×LOA
constrained waters (Kiel Canal)	6×LOA	1.6×LOA

2.2. Number and characteristics of detected incidents

The analysis of the ship domain violations within the Strait of Fehmarn-Belt produced a list of 229 cases during August 2014. During that period, 1516 unique vessels were underway in the investigation area. Table 2 lists the incidents categorised by the major vessel types.

Table 2

Violations of the ship domain in the Strait of Fehmarn-Belt categorised by major vessel types

Types of vessels involved in an incident	Count	Percentage
passenger vessel & passenger vessel	23	10%
passenger vessel & cargo vessel	71	31%
cargo vessel & cargo vessel	135	59%
Σ	229	100%

In most cases (59% of incidents), a violation of ship domain occurred when two cargo vessels were passing each other. This is followed by situations of cargo vessel approaching a passenger vessel (31% of cases), the incidents of two passenger vessels passing each other (10% of situations) is in third place. The high presence of the passenger vessels is related to a dense ferry traffic connecting Puttgarden, Germany, with Rødbyhavn, Denmark, and crossing the main inbound and outbound fairways connecting the Baltic Sea with the rest of the world. The locations of those incidents are shown in Fig. 5.

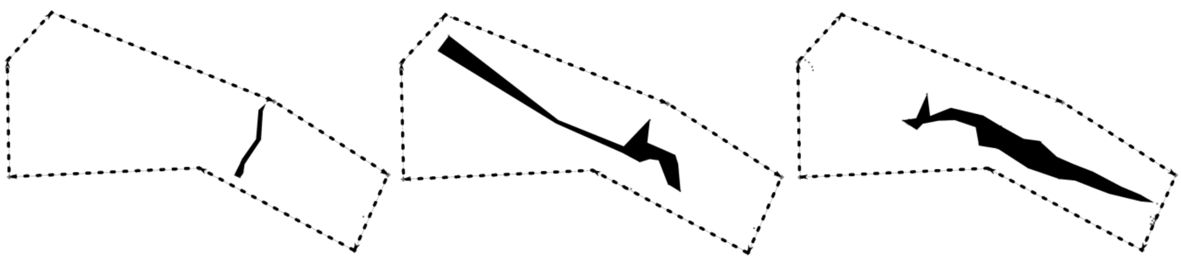


Fig. 5. The areas of the incidents involving two passenger vessels (left),a passenger vessel and a cargo vessel (middle) and two cargo vessels (right) in the Strait of Fehmarn-Belt

Rys. 5. Obszary występowania sytuacji zbliżeniowych z udziałem dwustatków pasażerskich (z lewej), statków pasażerskiego i handlowego (pośrodku) oraz dwustatków handlowych (z prawej) w Cieśninie Fehmarn-Belt

It can be observed that the incidents involving passenger vessels occurred mostly at the crossing area of the Danish - German ferry route and the main fairway of the Strait of Fehmarn Belt. The situations involving two cargo vessels, at a close distance, were located along Route T and its fork towards the Kiel Canal. The violations within the same set of vessels categorised by their overall length is shown in Table 3.

Table 3

Violations of the ship domain in the Strait of Fehmarn Belt
categorised by their overall length [own study]

LOA of vessels involved in an incident	Count	Percentage
50m—100m & over 100m	83	36%
over 100m & over 100m	141	62%
50m—100m & 50m—100m	5	2%
Σ	229	100%

The analysis of the ship domain violations within the Kiel Canal produced a list of 37532 cases throughout August 2014. A total of 922 unique vessels used the shortest route from the North Sea to the Baltic Sea during that month. Table 4 lists the incidents categorised by major vessel types.

Table 4

Violations of the ship domain in the Kiel Canal
categorised by major vessel types [own study]

Types of vessels involved in an incident	Count	Percentage
cargo vessel & cargo vessel	36240	96%
passenger vessel & high speed craft	2	<1%
passenger vessel & passenger vessel	8	<1%
cargo vessel & vessel engaged in towing	135	<1%
cargo vessel & high speed craft	31	<1%
cargo vessel & passenger vessel	1116	3%
Σ	37532	100%

Since the Kiel Canal is of fundamental importance to the European exchange of goods, it is clear that majority of incidents involved a pair of cargo vessels. The presence of passenger vessels is due to the touristic appeal of the canal. The ferries crossing the Kiel Canal also belong to this category of incidents. The violations within the same set of vessels categorised by their overall length is shown in Table 5.

In most of the cases, the overall length of two vessels passing each other at a close distance was longer than 50 meters. The occurrence of vessels smaller than that is related to the pleasure craft traffic. The example locations of the incidents between the longest vessels, which also highlight three sidings along the Kiel Canal in its north-eastern part are shown in Fig. 6.

Table 5

Violations of the ship domain in the Kiel Canal
categorised by their overall length [own study]

LOA of vessels involved in an incident	Count	Percentage
over 100 m & 50 m—100 m	17482	46%
12 m—50 m & over 100 m	142	<1%
12 m—50 m & 50 m—100 m	91	<1%
50 m—100 m & 50 m—100 m	7889	21%
over 100 m & over 100 m	11926	32%
below 12 m & over 100 m	2	<1%
Σ	37532	100%

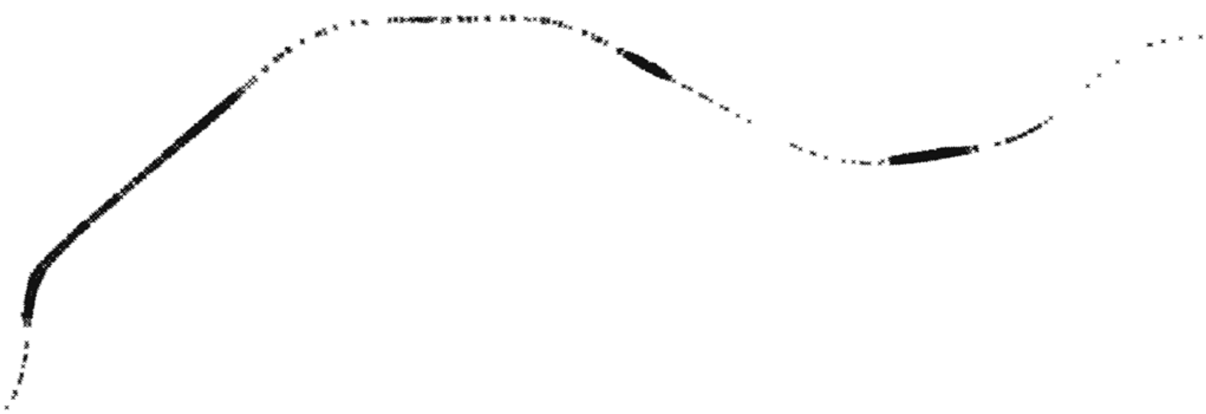


Fig. 6. The locations of the incidents involving a pair of vessels over 100 meters long each in the northeastern part of the Kiel Canal
Rys. 6. Położenie występowania sytuacji zbliżeniowych z udziałem dwustatków o długości powyżej 100 metrów na północno-wschodnim odcinku Kanału Kilońskiego

The analysis of incidents in the southern Baltic Sea, based on the AIS data of August 2014 covering both open and constrained waters, has shown numerous examples of ship domain violations. It is especially important not to jump to conclusions that the reason behind their occurrence is only related to bad seamanship or improper vessel handling. A safe distance between vessels is defined by various conditions prevailing within the area of navigation. But it may also be influenced by the judgement and decisions made upon incorrect PNT data of vessel. Therefore, it is of high interest to use the power of simulation in order to see how decision making on board can be influenced, by a certain allowed margin of errors within PNT data.

Regarding the constrained waters presented in the above investigation, it has to be emphasised that the vessel traffic in the Kiel Canal is strictly regulated based on the traffic group numbers. The pilotage including the canal helmsmen is compulsory for vessels which are not exempt from this requirement. Most of the vessels pass one another inside the sidings. There are also numerous ferries crossing the canal and avoiding other vessels at close distances. The violations of the ship domain in such a constrained and controlled environment have more of a pure geometrical nature, and less navigational delinquency.

3. SIMULATION BASED ESTIMATION OF NEED ON PNT DATA ACCURACY

The previous section showed with real world AIS data that the ship domain of Fuji [1] is not always a guaranteed area of free space for safety critical manoeuvres. Therefore, it is entitled to simulate vessel encounters violating the ship domain. These may lead to collisions in cases of missed situation awareness and can be caused by inaccuracy in the AIS/PNT data. Our idea is to investigate such situations, within an area of the size of a ship arena, to estimate requirements on the accuracy of maritime relevant PNT-data (COG, SOG, position).

3.1. Simulation Concept

In the maritime community, the need for resilient provision of PNT data is often focused on ship's position accuracy and integrity only. However, avoidance of collision by DSS requires that the current position, and movement of all ships within overlapping ship arena is monitored to evaluate their risk for collisions. Circular ship domains are sufficient to investigate, how accuracy of position, course over ground (COG), and speed over ground (SOG) of two ships could influence the detection or misdetection of potential collision risks between them. In this simulation approach, the accuracy of COG is associated with the accuracy of ship's true heading. More detailed analysis takes into account ship's shape, uses elliptical or polygonal ship domains, and requires a separate consideration of COG and heading errors. We decided to start our simulations with simplified modelling, using circles to describe ship arena, ship domain, and ship hull.

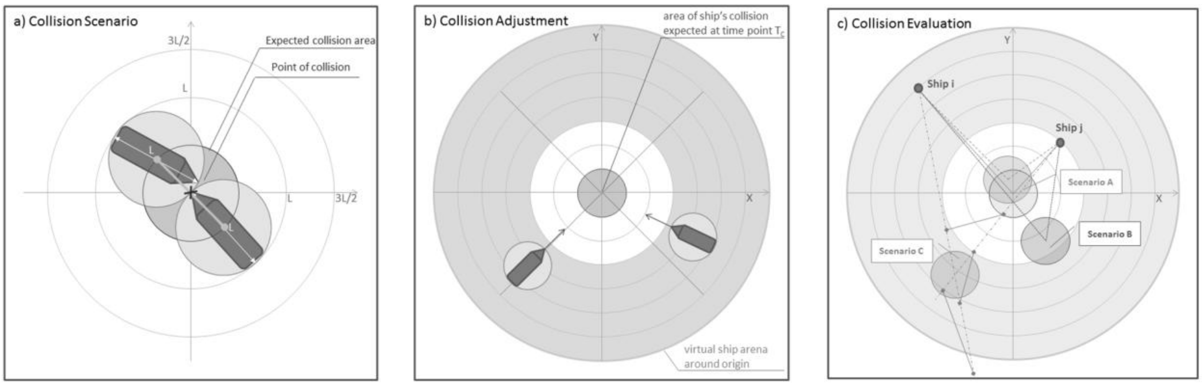


Fig. 7. Simulation concept
Rys. 7. Schemat przebiegu symulacji

The simulation concept is illustrated in Fig. 7. The ship hull is modelled as a cycle around ship's centre, with diameter in order of ship's length LOA. To simplify the simulation, we consider ships with equal ship length LOA=L. A collision between both ships occurs, when the modelled ship hulls abut or overlap (Fig. 7a). This is achieved, if the centres of both ships lie within a cycle with a diameter of L, hereinafter referred to as collision area.

As initialisation for all simulations, the "real" collision area is adjusted at origin of a coordinated system, whereby the time of collision is set on a fictive time point T_C=0. Furthermore, a virtual circular ship arena, whose centre is adjusted to the origin of coordinate system, is introduced. This virtual ship arena spans an area within which navigating as well as mooring ships should evaluate their own collision risk (Fig. 7b). The ship arena, proposed by Davis & Dove in [12], has a radius of 2.7 NM and specifies the maximum size of traffic area considered during simulations. This distance allows two ships moving towards each other at the SOG of 15 kn about 5 minutes to initiate and realise evasive manoeuvres. An individual ship, moving at 15 kn, needs no more than 20 minutes to pass the ship arena of other ships. During simulation, we consider only ships in the specified traffic area, of which true position, SOG, and COG fulfil the condition that the ship centre can arrive at the origin of coordinate system at the time point TC=0.

We assume that the ships (as potential parties of an accident in the "real" collision area) move linearly, without changing navigational parameters. Therefore, the movement of ship S_i (i=1, 2…I) is specified by the following formulas:

$$\underline{X}_i(t)=\begin{bmatrix} x_i(-\delta t_i) \\ y_i(-\delta t_i) \end{bmatrix}-\begin{bmatrix} \dfrac{x_i(-\delta t_i)}{\delta t_i} \\ \dfrac{y_i(-\delta t_i)}{\delta t_i} \end{bmatrix}\cdot(t+\delta t_i) \tag{1}$$

$$COG_i = a\,\boldsymbol{tan}2\left(-y_i(-\delta t_i),-x_i(-\delta t_i)\right) \tag{2}$$

$$SOG_i = \frac{\sqrt{y_i^2(-\delta t_i)+x_i^2(-\delta t_i)}}{\delta t_i} \tag{3}$$

where: $\underline{X}_i(-\delta t_i)$, SOG_i, and COG_i are the initial parameters for simulation of the movement of ship 'i' with

$$\sqrt{y_i^2(-\delta t_i)+x_i^2(-\delta t_i)} < 2.7\,NM\ . \tag{4}$$

A risk of an accident in the "real collision area" exists, if a second ship S_j (jε{1,2,…I}) can also achieve the origin of coordinate system at time point T_C=0. If both ships exchange their navigation data, via Automatic Identification System (AIS) sooner or later, the officers of the watch should recognize the origin as the Closest Point of Approach (CPA), with δt_i and δt_j as the Time to CPA (TCPA) in relation to ship S_i and S_j. A collision may occur if CPA is smaller than the dimension of the vessel. During simulation a collision is associated to abutting ship hulls. Consequently, the time to collision (ToC) is the earliest possible time point, at which the distance between both ship centres is smaller than the assumed ship length L:

$$\left|\left\|\underline{X}_i(t)-\underline{X}_j(t)\right\|-L\right| \Rightarrow \boldsymbol{min}\ , \tag{5}$$

Taking into account equations (1) to (3), the ToC is determined as

$$ToC_{i,j} = -\frac{L}{\sqrt{\left(\dfrac{x_i}{\delta t_i}-\dfrac{x_j}{\delta t_j}\right)^2+\left(\dfrac{y_i}{\delta t_i}-\dfrac{y_j}{\delta t_j}\right)^2}} \tag{6}$$

and will be achieved earlier than the simulated time point of collision T_C=0. The difference between ToC and T_C is a result of applied simulation model, and varies on dependence on initialised position, SOG, and COG of both ships.

Location and time point of a potential accident at origin can only be determined correctly, if the PNT data are provided with a certain level of accuracy. Therefore, inaccuracies of PNT data from both vessels (difference between true and indicated values) can result to misinterpretation or non-identification of existing collision risks, and the following scenarios can occur:

- Scenario A illustrates a situation (Fig. 4c), where the occurring inaccuracies are small enough to identify the simulated collision risk correctly. Due to negligible spatial and temporal shifts in relation to initialised collision area, the inaccuracies of PNT data are considered as tolerable. It can be expected that initialised evasive manoeuvres are based on correct situation awareness.
- With increasing inaccuracies of PNT data, the indicated collision area shifts more and more from the real collision area (scenario B). The needed evasive manoeuvres of both ships are conditioned

by faulty survey situation. Consequently, it cannot be expected that initialised evasive manoeuvres will really reduce the collision risk.

- Scenario C represents, more or less, the "worst case". The inaccurate PNT data shifts vessels' trajectories in such a way that the distance between both vessels is always larger than L. Therefore, an existing collision risk remains undetected, necessary evidence manoeuvres are not initialised, and an avoidable ship accident will take place.

The purpose of simulation is to determine bounds for tolerable inaccuracies of PNT data, based on more or less correct detection of initialised collision area (scenario A vs. scenarios B/C). These bounds can be used to evaluate requirements on PNT data provision from the perspective of collision avoidance.

3.2. Simulation setup

We perform 10^9 Monte Carlo simulations of vessel pair to determine the occurrence of scenario A, B or C, as described in the previous section. In order to check that the Monte Carlo simulations have converged, we performed 5 different runs which ended with similar results. Each situation consists of two vessels with a given position, SOG, COG, and the simulation time. The setup for each simulation is such that the time to collision varies between 5 minutes and 20 minutes, which should realistically allow the initialization of an evasive manoeuvre. The course of the two simulation participants is varied between 0 degree and 360 degrees, and the speed is set at a value between 0 knot and 25 knots. This configuration allows the determining of the start position of vessels, with the assumption that the origin of the coordinate system is the collision point. A subset of 10^5 vessels positions is shown in Fig. 8. The smaller subset size was necessary for visualization purposes.

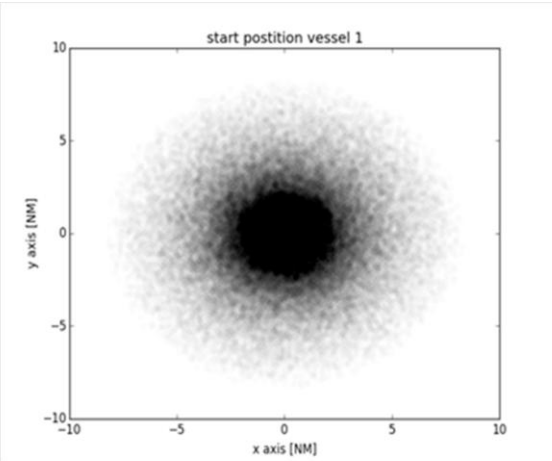


Fig. 8. Distribution of 10^5 starting positions
Rys. 8. Rozkład położenia 10^5 pozycji początkowych

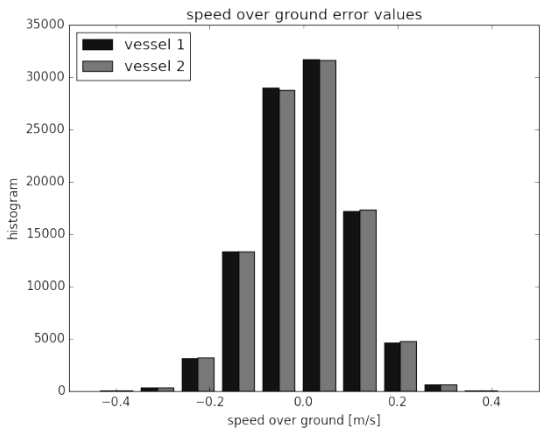


Fig. 9. Distribution of SOG error
Rys. 9. Rozkład częstości błędu prędkości nad dnem (SOG)

In order to generate realistic simulations, we verify that the initial positions of both vessels are not closer than 100 m, and/or the absolute difference of the COG is smaller than 5 degrees. This check guarantees the exclusion of simulations, where the initial condition is already in a collision state.

These parameters are sufficient to completely describe the simulated collision scenarios. Additional parameters are used to model the performance of the position, SOG and COG sensors. The position sensor is simulated with a two dimensional zero mean Gaussian distribution centred at the calculated true position. In order to investigate the influence of the sensor performance on correct detection of arising collision risks, we simulate different standard deviations for a two dimensional Gaussian distribution between 0 m to 30 m (10 bins).The error behaviour of COG and SOG sensor is simulated with a zero mean Gaussian distribution, with standard deviations differing between 0 degree and 1degree (10 bins) in the case of the COG sensor, and between 0 to 0.2 knots (10 bins) in the case of the SOG sensor. Fig. 9 shows the histogram of the SOG error distribution of a subset of 10^5 simulations for the two simulated vessels. The simulation parameters are summarized in Table 6.

Table 6

Simulation parameters

Parameter	Value range	Description
SOG_i	0 .. 25 kn	Speed over ground (SOG)
COG_i	0 .. 360 DEG	Course over ground (COG)
δt	5 .. 20 min	Time to Collision
N_{tot}	109	Number of simulations
σ_{pos}	0 .. 30 m (10 bins)	Gaussian Error of position
σ_{SOG}	0 ..0.2 knots (10 bins)	Gaussian Error of SOG
σ_{COG}	0 .. 1 DEG (10 bins)	Gaussian Error of COG

3.3. Simulation results

This section presents initial simulation results. The plots in Fig. 10 show the frequency of scenario A, B, and C, as a function of the sensor performance. The black solid line in each plot represents scenario A, where the occurring inaccuracies are small enough to ensure that the collision risk is identified correctly. The black dashed line represents scenario B, where the increasing inaccuracies of PNT data result to a shift of the collision area. Finally, the black dashed dotted line represents scenario C, where the inaccurate PNT data shifts vessels' trajectories in such a way that the collision is not detected. The solid dark-grey line illustrates the combination of all 3 scenarios and should sum up to unity, which is the case for all performed simulations. The solid light grey line illustrates the 1% risk-level boundary; crossing the light- grey line means that the risk of a scenario to occur is greater than 1%.

Fig. 10a shows the result for different simulated inaccuracies of position sensor, while the upper right (b), and lower left (c) plot present the results for different inaccuracies of SOG and COG sensors.

Fig. 10d shows the result of a more realistic simulation, in which different inaccuracies of position sensor is simulated, in combination with inaccurate SOG and COG (standard deviation SOG = 0.1 knots; COG=0.1 DEG. In summary, all figures show the same trend. The risk that scenario C could occur is minimal for the highest sensor performance (smallest standard deviation), and rises with increasing inaccuracies of the considered sensor data. It should be noted that the risk that scenario B could occur stays, more or less, constant in all four simulations.

If it is required that the probability of scenario C should be below 1%, then it is necessary that

- σ_{pos} should be smaller than 27 m (Fig. 10a),
- σ_{SOG} should be smaller than 0.09 knots (Fig. 10b), and
- σ_{COG} should be smaller than 0.25 DEG (Fig. 10c).

Additionally, it can be seen in Fig. 10d that in the case of the combined error, it is not possible to keep the probability of occurrence of scenario C below 1%.

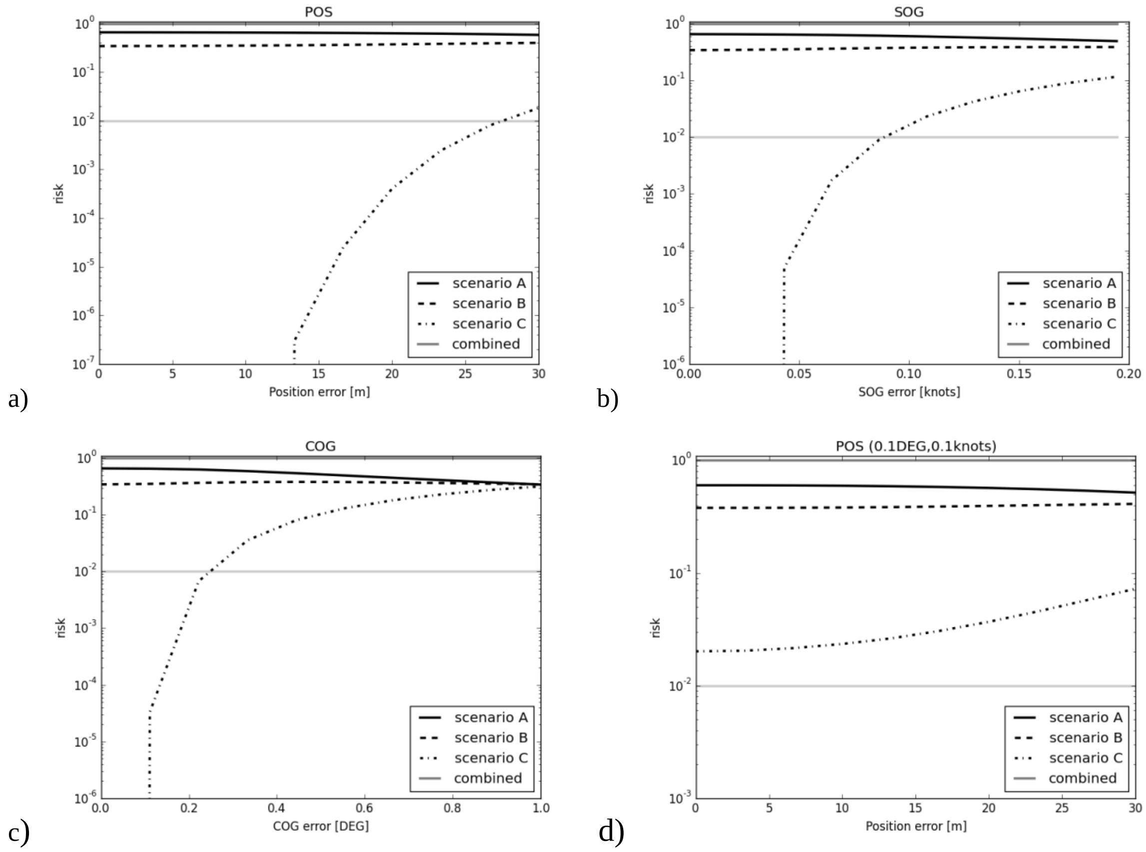


Fig. 10. Frequency of occurrence of scenario A, B, C as function of the position error (a – upper left), SOG error (b – upper right), COG error (c – lower left) and position error with nonzero SOG and COG standard deviation (d – lower right)

Rys. 10. Częstości występowania scenariuszy A, B oraz C jako funkcje: błędu pozycji (a), błędu prędkości nad dnem (b), błędu kursu nad dnem (c) oraz błędu pozycji z niezerowymi odchyleniami standardowymi prędkości i kursu

A position error (95%) of 100 m such as required for vessel navigation on oceans by IMO is more or less compliant with the result of Fig. 10a. However, the main conclusion from initial simulation is shown in Fig. 10d, and documents the necessity to consider all contributing error sources (error propagation as well as overlapping), if accuracy of individual data will be specified.

4. SUMMARY AND CONCLUSIONS

This paper addresses to what extent collected AIS data, and simulation of collision scenarios, could be used to derive accuracy requirements on shipborne provision of PNT data.

In the last decade, the concept of ship domain has been introduced to describe the safety area around a ship, which should not be violated by obstacles or other traffic participants. First, models were derived from best practice and good seamanship. Further models of ship domains have been created differing in shape (e.g. circular, elliptical, hexagonal, and polygonal), and distinguishing between sharply delineated domains and fuzzy domains to indicate one or more safety areas. In our studies, we decided to start our investigations with classic models.

For the simulations, it is important that the subject under investigation corresponds to events or phenomena taking place under real world conditions. Therefore, a comprehensive analysis of AIS data, collected in the southern Baltic Sea, has been performed to assess the approaches between real vessels in relation to the violations of their ship domains, and the types of areas they navigate. The AIS data of August 2014 has shown numerous examples of ship domain violations. The fact that the vessels come close enough to enter the smallest ship domain specified in the literature shows that a collision risk might exist. This allows us to ask what navigational sensor performance is needed to make such close encounter situations safe. With the Monte Carlo simulations, we investigated the case of undetected collisions. This means that a simulated collision cannot be detected at the correct time, and/or at the right position, as a result of less accurate PNT data exchanged via AIS. The results of the simplified simulations show that it is possible to limit the risk of not detecting a collision, by increasing the accuracy of sensor data. However, in the case of the more realistic combined error of all navigational sensors, it is not possible to reduce the rest risk of not detecting the collision to less than 1°. This simulation, especially, documents the necessity to consider all contributing error sources (error propagation as well as overlapping), if requirements on accuracy of individual data should be specified.

It should be noted that simulation simplifies the real situation by linearizing the vessel movement, assuming Gaussian sensor noise with no systematic offset, uncorrelated error behaviour, and without considering any possible intervening manoeuvre.

The results can be summarized as follows: the AIS data shows that close encounter situations happen in the observed areas. The simulations show, under the assumed restrictions, that there is a non-negligible risk of not detecting a collision, if inaccuracies of sensor data, as well as aspects of error propagation and overlapping remain unnoticed. Finally, this leads to the next steps where we would like to improve the simulations to more realistically describe the real world situation. These improvements will include non-linear movement models, non-Gaussian noise, and intended evasive manoeuvres.

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